ENHANCEMENT OF THE REMOTE FIELD EDDY CURRENT TESTING PERFORMED FROM OUTSIDE OF A MAGNETIC TUBE

T. Marek, D. Gombárska

Department of Electromagnetic and Biomedical Engineering, Faculty of Electrical Engineering, University of Zilina, Univerzitna 1,010 26 Zilina,
e-mail: gombarska@fel.utc.sk, marek@fel.utc.sk

Summary The paper deals with design of remote field eddy current probe for non-destructive testing dedicated for inspection of ferromagnetic tubular material from outside. The remote field effect inside the tube wall is achieved by the medium of a magnetic shield covering the probe. Results of numeric simulations made for verification of probe characteristics confirmed the effectiveness of probe design.

1. INTRODUCTION

Non-destructive testing (NDT) is utilized to examine structural components because of localization and characterization of material properties' degradation (i.e. crack) that might cause malfunction of a component (e.g. reactors to fail, trains to derail, pipelines to burst, etc.) with economical and ecological impacts. The NDT is performed to assure consequent faultless operation of an inspected object without any mechanical damage. Recently, NDT methods are used not only for localization of a crack, but also for characterization of its size, shape, and orientation.

This paper concentrates on the eddy current non-destructive testing (ECT) and especially on the remote field eddy current testing (RFECT) method. Numerical simulations of electromagnetic field distribution using the finite element method are done to simulate inspection of a tubular specimen with a defect of a variable depth and width.

The traditional ECT methods are based on the measurement of impedance of the probe coil. When an alternating electromagnetic field of a given frequency, produced by the alternating current, is applied to a conductive object, the induced eddy currents in the object alters the field and the total flux linked with the coil. Therefore, the coil impedance of an ECT probe is a function not only of the coil parameters, but also of the object conductivity, relative permeability and geometry, which means that the impedance of the ECT probe depends on the material properties of the object under inspection [1]. Anomalies on the surface of the object also alter the induced current, which leads to changes of the probe coil impedance.

Another approach consists in using a probe with two coils. The first coil is a field coil intended only for generation of electromagnetic field while the second one is a measuring coil (called a pickup coil in the ECT terminology). The principle of functioning is identical, but the anomalies of the object under inspection alter induced voltage in the pickup coil that is measured.

The RFECT is widely used method of magnetic tubes inspection, which is based on ECT reflection probe with the pickup coil placed in the remote field zone [2]. The main advantage of the method is its almost equal sensitivity to defects situated inside (ID) and outside (OD) of the tube.

The RFECT method has been mainly used for the inspection of tube wall from inside the tube. But in some cases the possibility to access the inside of the tube is limited even impossible. Therefore the inspection must be done from the outer side of tube.

Several studies proposed to enforce the remote field effect from the outer side of the tube by appliance of the shielded probe. Although successful results were reported [3], the studies consider only nonmagnetic tubes.

The basic two coils configuration (one exciter, one pick-up) with merged shield is proposed here. Material and dimensions of the shield, distance between the coils as well as exciting frequency are optimized. Also robustness of the probe against various changes in material parameters and lift-off change is verified here.

2. DESIGN AND OPTIMIZATION OF THE PROBE

The purpose of this study is the design and optimization of the RFECT probe for inspection of a magnetic tube with the outer diameter of 0.5 m, the wall thickness of 10 mm and the material parameters $\sigma = 1MS/m$, $\mu_r = 100$ from its outer surface [4]. Whole circumferential wall thinning is used to model a defect arising from the inner or the outer surface of the tube.

Several parameters are variables in process of design and optimization of the probes' configuration, i.e. material, configuration and dimensions of shield; arrangements of coils, their dimensions and distance between them; and finally the exciting frequency. Using numeric simulations of several coil arrangements it has been found out, that arrangement of the coils, i.e. number of exciters and pick-ups, and width of coils do not play important role in the probe design. Therefore simple configuration with one exciting coil and one pick-up coil is considered. In such case the dimensions of the probe can be easily minimized.

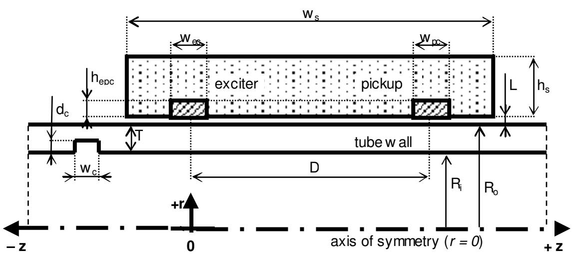

Fig.1 Configuration of the RFECT probe with one merged monolithic shield made of cobalt

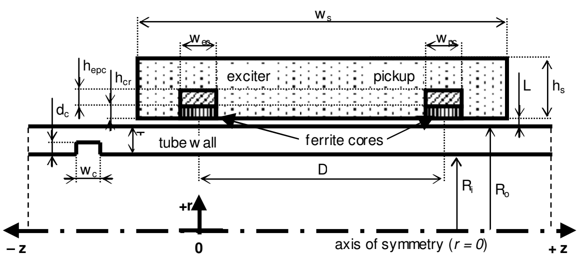

Fig.2 Configuration of the RFECT probe with cobalt shield and ferrite cores

OPTIMIZATION OF THE SHIELDING MATERIAL

Two materials for shield are chosen for further investigation, cobalt (Co) and copper (Cu). Their electromagnetic properties are listed in Table 1. The configuration of the probes' shield is designed as one merged shield covering both the coils (Fig. 1). The compound shield configuration made of Co and Cu, where the body of the shield is made of Cu and the area around the exciter coil is filled with Co, bring not reasonable results. It was found that more complex covering shield structure made of two or more materials bring more complex pickup signal.

Table 1. Material properties used in simulations

Material	σ_s [*MS/m*]	μ_{rs}
Cu	*58*	*0.999991*
Co	*16*	*68*

Two cases of the monolithic shield are studied, a one without (Fig. 1) and one with (Fig. 2) ferrite cores beneath the probe coils. The simulation results for optimal selection of shielding material leads to conclusion that the pure Co has better characteristic than the pure Cu in order to reach the RFECT effect. Therefore, monolithic shield made of Co is used for the final design.

In the parallel study of the probe with ferrite cores placed beneath each of the coil (Fig.2) it is supposed that the ferrite cores might be helpful in suppressing of the near field. The simulation results proved the effectiveness of the inserted ferrite cores; however the amplitude of pick-up signal (Fig. 4) is considerably reduced in comparison with the pure Co shield without the cores (Fig. 3). Although, differences between ID and OD signals in case of Co+ferrite shield are smaller. Thus, both the configurations of the probe with Co merged shield are chosen for further optimization process.

OPTIMIZATION OF THE PROBE DIMENSIONS

The minimum distance between the coils is the key parameter influencing outer dimensions of the shield and though dimensions of the probe. It should be noted that there is a relationship between the distance of the coils and a width of detectable crack by remote field effect. The optimization process is done for both the probe types (for pure Co and for Co+ferrite shields). Table 2 summarizes variables which are changed.

Table 2. Variables used in optimization of probe

Variable	Interval	Step
Coil distance	70mm-90mm	5mm
Defect width	1mm, 5mm-50mm	5mm
Frequency	100Hz-400Hz	100Hz

Two criteria are defined to evaluate the gained results; minimal phase and amplitude differences between signals of ID and OD defects are used to find the optimal configuration. The simulation results show that the maximum width of detectable crack rises with the distance of the coils, but the amplitude of the pick-up signal decreases with the coils distance. The outer dimensions of the shield should be adjusted based on a chosen distance between the coils to minimize unwanted edge signals. The distance between the shields' edge and the coil should not be less than 25mm.

The configuration of the proposed RFECT is shown in Fig. 1, 2 and its optimal dimensions are summarized in Table 3.

The signals of ID and OD defects with a constant width of 20 mm growing from 0 to 100% are calculated for the final configuration of the probe. The dependencies of the signal amplitudes and phases are shown in Fig. 7, 8 for the probe without and with the ferrite cores beneath the coils, respectively.

Table 3 The final dimensions of probe

Variable	Dimensions
Cobalt shield	ws = 130 mm, hs = 15 mm
The coils distance	D = 80 mm
The coil dimensions	wec=wpc=3mm, hepc=2mm, * hcr=1mm
Exciting frequency	f = 300 Hz
Lift-off	L = 0.5 mm

* Valid only for case of Co+ferrite shield

3. SIMULATION RESULTS

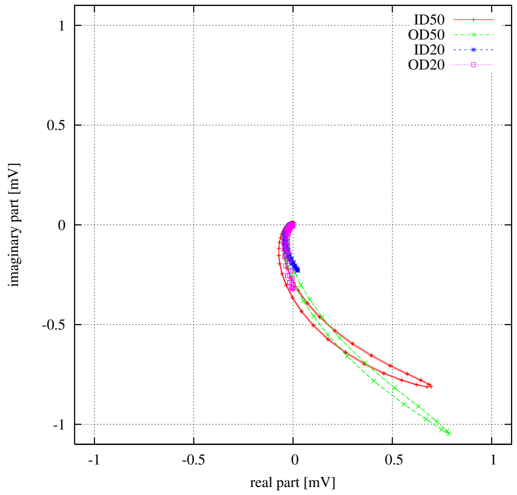

Fig.3 Lissajous plot of the pick-up signal, simulations of the probe with Co shield, f = 300 Hz, D = 80 mm and wc = 5 mm

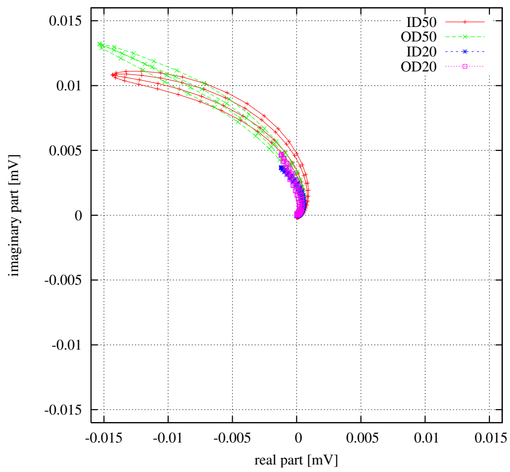

Fig.4 Lissajous plot of the pick-up signal, simulations of the probe with Co+ferrite shield, f = 300 Hz, D = 80 mm and wc = 5 mm

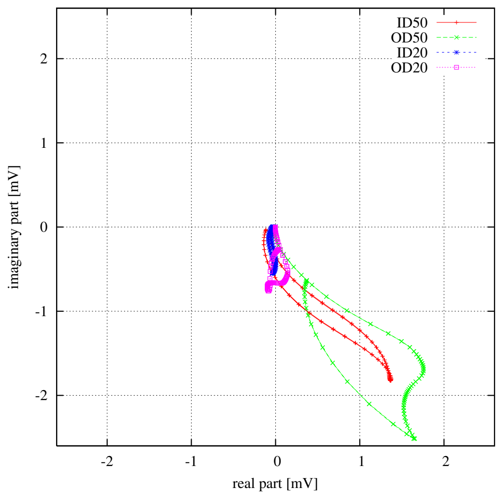

Fig.5 Lissajous plot of the pick-up signal, simulations of the probe with Co shield, f = 300 Hz, D = 80 mm and wc = 40 mm

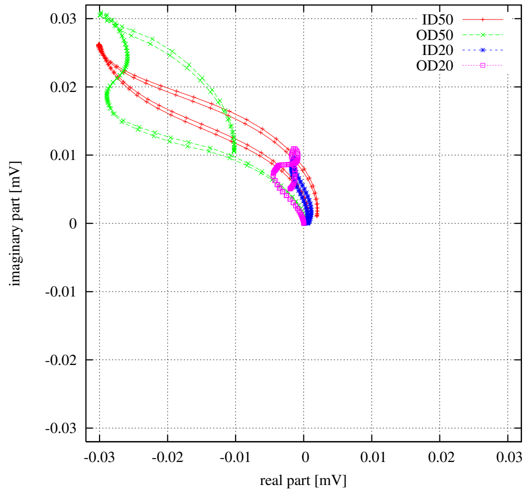

Fig.6 Lissajous plot of the pick-up signal, simulations of the probe with Co+ferrite shield, f = 300 Hz, D = 80 mm and wc = 40 mm

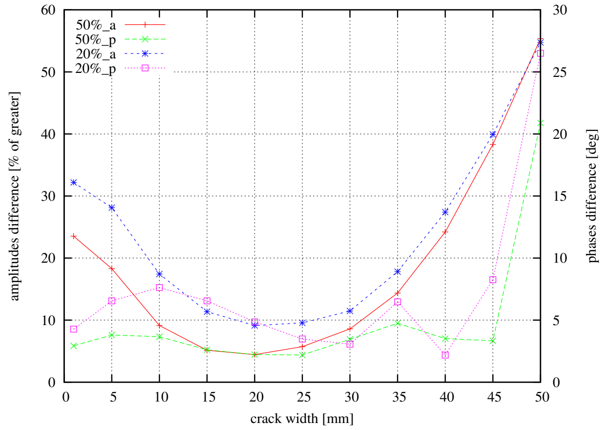

Fig.7 Effect of the crack width, the probe with Co shield, f = 300 Hz, D = 80 mm on differences of amplitudes, in % of greater value, and absolute differences of phases between OD and ID signals

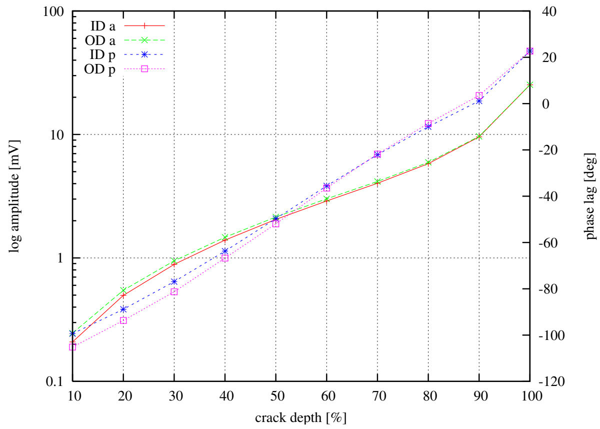

Fig.9 Amplitude of the pick-up signal (log scale) and its phase depending on the crack depth, the probe with Co shield, ID/OD 10%-100% cracks, f = 300 Hz, D = 80 mm and wc = 20 mm

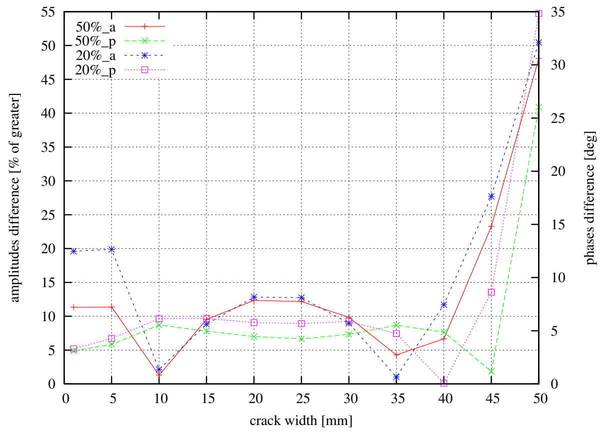

Fig.8 Effect of the crack width, the probe with Co+ferrite shield, f = 300 Hz, D = 80 mm on differences of amplitudes, in % of greater value, and absolute differences of phases between OD and ID signals

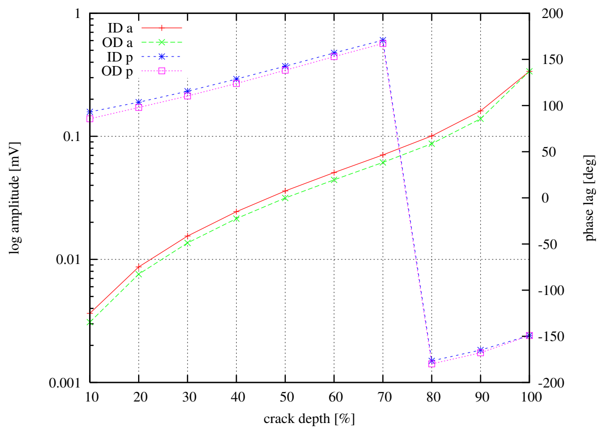

Fig.10 Amplitude of the pick-up signal (log scale) and its phase depending on the crack depth, the probe with Co+ferrite shield, ID/OD 10%-100% cracks, f = 300 Hz, D = 80 mm and wc = 20 mm

4. CONCLUSION

The aim of the study was to enhance the remote field eddy current testing performed from outside of the magnetic tube by optimization of the RFECT probe configuration. In order to reach RFECT effect it was necessary to use the probe with appropriate shield. Among several configurations of the probe explored in the project, the simple outer reflection probe type (1 exciter – 1 pickup) was chosen for the study as others do not bring any significant advantages; moreover more complex signals are obtained when the multiple coil design is used.

The configuration of the merged shield covering both the coils was proposed in this project. Numerical simulations were used for examination of two shielding materials – copper and cobalt.
Whereas the copper shield causes significant reduction of the signal amplitude the shield made of cobalt was chosen for the final configuration.
In order to further suppress near field effect, the cobalt shielded probe with ferrite cores placed beneath the coils was also investigated. Both the configurations, i.e. monolithic cobalt shield with and without the ferrite cores beneath the coils, were simulated for variable ID and OD crack widths, distances between the coils as well as different frequencies of 100, 200, 300 and 400Hz to find their optimal values. The optimized configuration of the probe with and without ferrite cores shows very good performances. The proposed probe is quite robust against fluctuation in material properties of the tube and the shield; however increased lift-off causes loss of remote field effect.

Acknowledgement

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